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Experiment study of oil tank fire characteristics dependent on the opening of tank top

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Abstract

In order to study the influence of top opening on oil tank fire characters, small scale oil tank fire experiments with 1, 1/2, 1/4 ,1/8 opening proportion factors (opening area / tank top area) and different opening eccentricities (opening centroid position to the center of a circle) were carried out in a still environment. The mass loss rate, flame radiation and images, tank-shell temperature were recorded. The results suggested that, the oil tank fire characteristics varied with the opening proportion factor of tank top. Comparisons between the combustion behaviors of partly open oil tank fire and fully open pool fire with the same equivalent diameters showed that, the mass loss rates and flame frequencies of tank fires were almost consistent with pool fire. But flame shape varied with the opening proportion factor and eccentricity, for partly opened oil tank fire, the flame shape is unsymmetrical but L-shaped, and flame height showed difference with pool fire as flame height gets lower when opening proportion factor approaches 0. We compared the flame radiation and tank-shell temperature of open end side and opposite side, found the difference and inferred the significant causes leading to the difference were opening proportion and opening eccentricity.

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Keywords: Opening proportion; Tank fire; Flame shape; Opening eccentricity; Pool fire

Nomenclature

D	equivalent diameter (m)
f	fire frequency (s^{-1})
k	opening proportion
L	flame height (m)
$\dot{m}$	mass loss rate (g/s)
$\dot{Q}$	heat release rate (J/s)
$\dot{q}''$	flame radiation (W/m^2)
S_0	tank top area (m^2)

1. Introduction

Oil tank fire with plenty liquid fuel has strong radiation and high flame, which is a big disaster and hard to control. In order to improve the method of putting out oil tank fire, it is necessary to study the tank fire characteristics. Vertical cylindrical tank, including the dome roof type and the floating roof type, are the most commonly used metal storage tank. Oil tank fire was often caused by oil leakage with a very small fissure, but continuous fire combustion and air entrainment may cause the combustible fuel gas under the tank top explode. As the tank top was destroyed by the explosion, different

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openings appeared. Dome roof tank top would be totally opened or nearly to totally opened, while floating roof tank top always only occurs cracks on the edge of the oil tank top where just is the weak place [1, 2]. The fact that, in dome roof tank, the pressure of the volatilization gas oil is difficult to control, leakage and explosion accidents usually happen [3, 4], large oil tanks usually are floating roof tank.

In terms of the floating roof tank fire with partly opened top, as the liquid fuel was partly open to air, partly under the metal top, so fuel vaporization, air entrainment and heat feedback were different from fully opened tank fires which are often simplified as pool fire. But most previous experimental and theoretical studies were confined to fully open pool fires. Only several researchers measured the mass loss rate of the oil tank fire in partly open condition [5, 6]. However, they only obtained the mass loss rate, with no measurement on other important parameters, and they simply thought that mass loss rate is approximately linearly with open area.

In this paper, we measured mass loss rates, flame heights, fire frequencies of small scale oil tank fire with different openings. Opening proportion and opening eccentricity factors were introduced to describe the partly open conditions of oil tank. Then we compared the experiment results of partly open oil tank fire with fully open pool fire theoretical predictions. Finally the experiential formula was improved based on the characteristics of oil tank fire. And we discussed the difference of flame radiation and tank-shell temperature for open end side and opposite side, and found the influence of opening eccentricity on the flame surrounding environment.

2. Experimental

Flexible conditions and precise measurements are very difficult for full-scale oil tank burning test, so we set a small scale oil tank fire experiment. Oil tank fire characteristics include many aspects, for instance flame heights, mass loss rate, flame shape etc. Mass loss rate decides the other fire characteristics to some extent, while the flame height is the most intuitive phenomenon once a fire breaks out. We set an experimental scene in an open environment without wind, as shown in Fig. 1.

The experimental oil tank was designed for vertical cylindrical tank, 30 cm in diameter, 25 cm in height (same proportion to the oil tank of 3000 stere, which diameter is 17.14 m, high is 14.53 m), and without roof. Meanwhile, made three incomplete circular plates of 30 cm in diameter which could just covering the tank with opening proportions of 1/2, 1/4 and 1/8 respectively, as shown in Fig. 2.

Put an electronic balance under the oil tank to measure the mass loss. Two thermal radiometers are respectively decorated in open end side and the opposite side where the distance between the tank's centre was 5 times diameter of the tank, and keep parallel to the tank top. Similarly, two thermocouples were clinging to the external wall of oil stank with insulating stretch tight balteums in open end side and the opposite side, and keep parallel to the liquid level. A video camera was used to record the flame image while there was a vertical ruler placing behind the tank, so we can get flame height through the video. The experiment mainly used diesel, however, we blended 10% gasoline in order to make it easier to be ignited. To simulate the storage of oil in floating roof tank, it was necessary to reduces volatile space. So we poured mixed diesel into the tank until the liquid level from the tank top was only 1 cm. There were four test groups, burning without cover and burning with three different opening proportion covers on the tank. For the three test groups which had cover on it, make sure the open apertures were in the same direction towards the tank. So the relative opening eccentricity was gradually increasing. However, in the tests which had 1/4 and 1/8 opening proportion covers, it will inevitably encounter the phenomenon of oil can't be ignited. In these cases, we ignited the oil first, and then put the cover on the tank. In order to reduce the random error, each group of test should be taken three times, take the average as the result of the experiment.

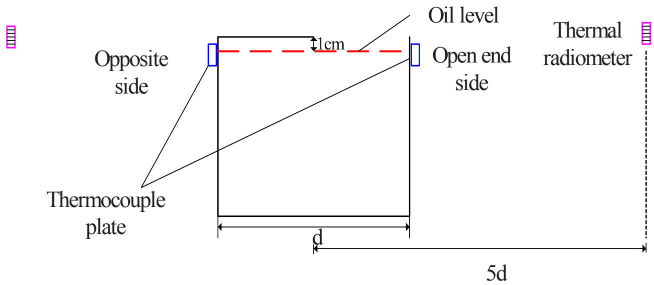

Fig. 1. The schematic of small scale oil tank fire experiment.

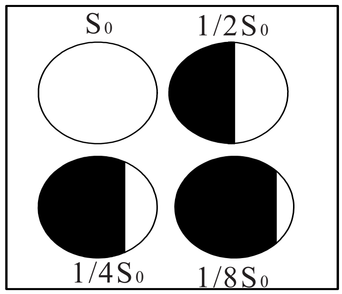

Fig. 2. Opening proportion and opening eccentricity of tank top.

3. Results and discussions

3.1. Mass loss rate

The mass loss rate is a basic parameter of oil tank fire. In order to reflect mass loss rate ($\dot{m}$) changed as opening proportion changed, the relation table of $\dot{m}$ with different opening proportion is showed here. Specifically, let k denote the opening proportion of tank top. In this case, Table 1 gives the mass loss rate of oil tank fire at a series of opening proportion for 1, 1/2, 1/4 and 1/8.

Table 1. The mass loss rate of oil tank fire at a series of opening proportion

k	$\dot{m}$ (g/s)
1	0.810
1/2	0.403
1/4	0.099
1/8	0.040

As shown in Table 1, $\dot{m}$ increased with the increase of opening proportion. To analyze the effect of opening proportion on $\dot{m}$, compared the result with formal researcher's work. Blinov et al. [7] did a lot of pool fire experimental research, a series of burning rate curves of different fuels were obtained, as shown in Fig. 3.

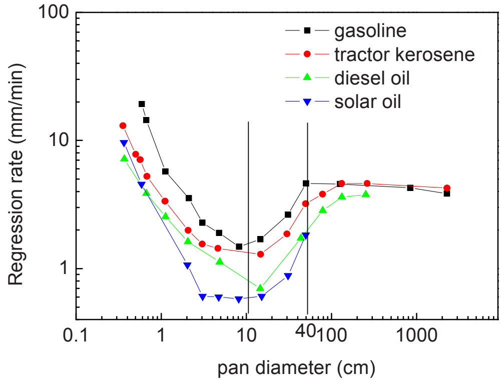

Fig. 3. Regression rate and flame height date for liquid pools from blinov and khudiakov.

Tu et al. [8] found that, for pool fire which equivalent diameter between 10~50 cm, dimensionless heat release rate $\dot{Q}^*$ keeps constant for the same fuel. It could be expressed by formula as

$$\dot{Q}^* \propto \frac{\dot{Q}}{D^{5/2}} = constant \tag{1}$$

here, $\dot{Q}$ is the heat release rate, D is the equivalent diameter. The formula could be changed into

$$\frac{\dot{m}}{D^{5/2}} = constant \tag{2}$$

So $\dot{m}$ is in proportion to $D^{5/2}$ for pool fire. We assume that this formula is also work for oil tank fire. Use k and tank top area S_0 to replace l, we get a formula like this

$$\frac{\dot{m}}{D^{5/2}} \sim \frac{\dot{m}}{(\sqrt{S_0 \cdot k})^{5/2}} = constant \tag{3}$$

In this paper, S_0 is a constant, so the formula could be change as

$$\frac{\dot{m}}{D^{5/2}} \sim \frac{\dot{m}}{k^{5/4}} = constant \tag{4}$$

For proving Eq. (4) availability for tank fire, we use the date in Table 1 to build a relationship between $\dot{m}$ and $k^{5/4}$ as shown in Fig. 4. The goodness of the fitting, namely the R, is also given. We can see the mass loss rate has good linear relationship with $k^{5/4}$. The maximum deviation between the experiment result and the linear fit curve happens when $k = 1/2$, experiment result is obviously above the fitting curve. While k get smaller than 1/4, experiment results are under the curve. That's because oil level under the tank top 1cm distance, so the real fire area may differ from the opening area. When $k = 1/2$, the real fire area is larger than the opening area, it lead to more fuel consume. While $k < 1/4$, fire area seems small compared to oil surface area, most of the combustion heat was used to keep surrounding oil warm, so mass loss rate decreased.

Additionally, in order to verify whether the formula applies to large scale oil tank fires, built a relationship by experimental results of former researchers [9]. They did a similar experiment in 2000, which tank diameter was 1m. As shown in Fig. 5, identically, the mass loss rate has good linear relationship within $k^{5/4}$. So the conclusion is applicable for the larger scale oil tank fire case too.

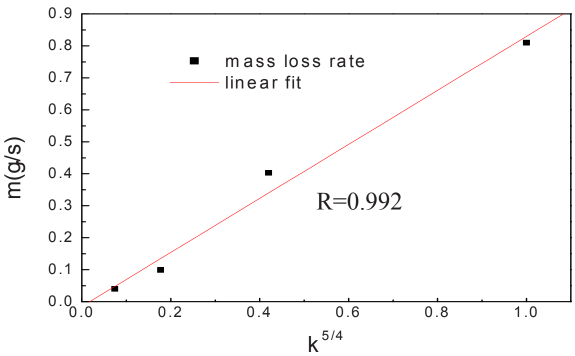

Fig. 4. The mass loss rate of oil tank fire at a series of opening proportion.

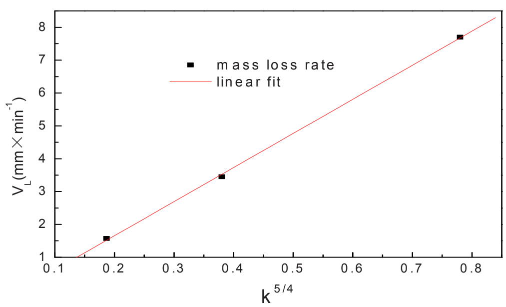

Fig. 5. The mass loss rate of oil tank fire at a series of opening proportion for 1 m diameter.

3.2. Flame height

The flame height changed when the opening proportion of tank top changed. Fig. 6 shows the corresponding flame height at a series of opening proportion. It could be seen that, as the opening became small, the flame height dropped obviously. In order to get the flame height accurately, we used fast Fourier transform to time variation of image correlation coefficients of a continuous image sequences, then use Tecplot to calculate flame height.

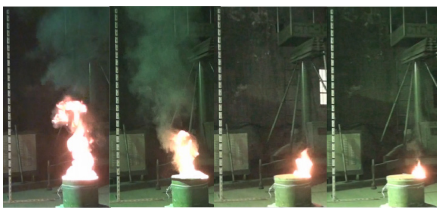

Fig. 6. The flame height of oil tank fire at a series of opening proportion.

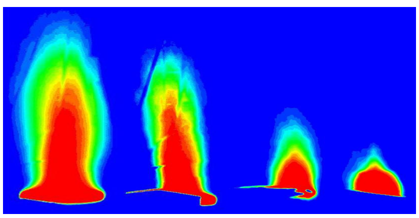

Fig. 7. Probability distribution of flame at a series of opening proportion.

Figure 7 shows the flame images after processing by Tecplot. The different colours in the graph represent different probabilities, and the higher the probability, the deeper the red colour. According to flame height definition, choose the appearing probability of 50% as the flame height. We got the flame height of oil tank fire at a series of opening proportion as shown in Table 2.

Table 2. The flame height of oil tank fire at a series of opening proportion

K	*L* (m)	*D* (m)
1	0.7	0.3
1/2	0.575	0.212
1/4	0.22	0.15
1/8	0.273	0.106

For pool fire, there is an empirical formula for flame height calculation [12]. The formula can be written as:

$$L = 0.235(\dot{m}\cdot\Delta H)^{2/5} - 1.02D \tag{5}$$

here L is flame height, $\dot{m}$ is mass loss rate, ΔH is the heat of combustion, D is equivalent diameter. As in previous analyses, when the tank top is totally opened, it has no difference with pool fire, so the flame height should be agree with Eq. (5). But whether it's suitable for tank fire flame height while the tank top only partly opened, it still needs to be verified by experiment.

The mass loss rate can be found in Table 1, ΔH for diesel is 44.8 × 10^3 kJ/kg. Fig. 8 shows the trends of experiment date and calculation changed with *k*. It's found that when *k* is large enough, the calculation fit the experiment result well, but experiment result is lower than calculation significantly when k approaches 0. This phenomenon can be interpreted as the first part in the right of Eq. (5) has changed. $(\dot{m}\cdot\Delta H)$ could be seen as $\dot{Q}$,the heat release inside unit time. For pool fire and tank fire when tank top is totally opened, $\dot{Q}$ is complete use for sustaining combustion. But when tank top just partly opened, the heat release is not only use for sustaining combustion but also keeping surrounding liquid high temperature, so actual heat use for sustaining combustion is less than $\dot{Q}$. The flame height gets lower when *k* approaches 0, because the smaller *k* is, the actual heat use for sustaining combustion is little.

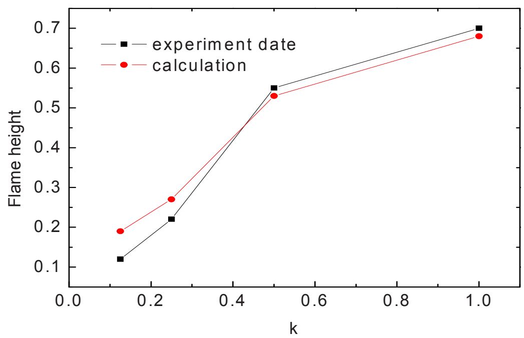

Fig. 8. The flame height of oil tank fire at a series of opening proportion.

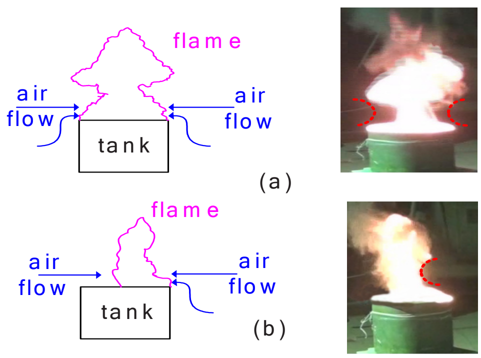

Fig. 9. Relative position of flame to the tank.

3.3. Flame shape and fire puffing frequency

When $k = 1$, the tank fire's flame shape was very similar to that of pool fire. However, while $k \neq 1$, there are remarkable difference between tank fire and pool fire. This is due to the influence of tank body to the fire environment. Fig. 9 (a) shows the flame shape when the tank top is totally opened, the air flow around the flame is well-proportioned, so the flame shape is symmetrical and just like the flame of pool fire. When the tank top isn't totally opened but just open in one side, the tank restricts the air flow below the opposite side of the aperture, air flow around the flame is uniform. Fig. 9 (b) shows the flame shape when $k = 1/2$, the flame shape is asymmetric; fire puffing mainly happen in the open side, flame shows unsymmetrical but L-shaped.

This phenomenon can be more clearly observed by Fig. 10, which shows sequential flame images after binarization in a cycle of flickering movements when $k = 1$ and $k = 1/2$. As is shown in the picture, we can see that when $k = 1$, both side of the flame have signally puffing; when $k = 1/2$, puffing only happens in the right side.

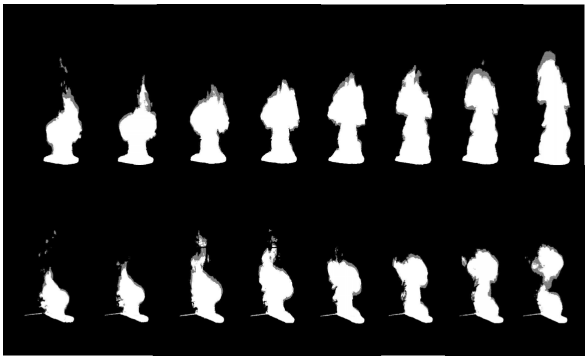

Fig. 10. Sequential flame images in a cycle of flickering movements for $k = 1$ opening and $k = 1/2$.

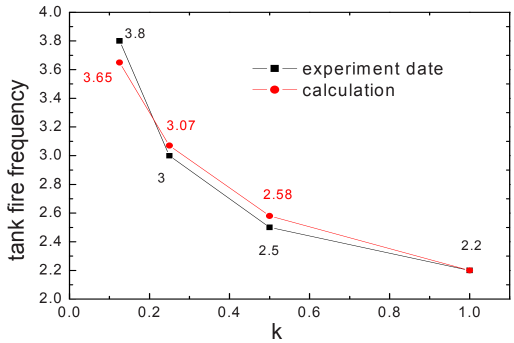

Fig. 11. The fire frequency of oil tank fire at a series of Proportion.

Former researchers found an equation to predict fire puffing frequency for pool fire, as shown in the flowing.

$$f = C\sqrt{\frac{g}{D}} \tag{6}$$

here C is a proportionality factor, for the majority fuel, C is suggested to be approximately 0.48 according to experimental data, but for diesel the calculations overestimate the f [10, 11]. Table 3 gives the puffing frequency of oil tank fire and equivalent diameter at a series of opening proportion for 1, 1/2, 1/4 and 1/8.

Table 3. The puffing frequency and equivalent diameter at a series of opening proportion

k	f	D (m)
1	2.2	0.3
1/2	2.5	0.212
1/4	3	0.15
1/8	3.8	0.106

Because the tank fire flame has the same shape to the pool fire flame when tank top is totally open, take f and D to Eq. (6) to account C while $k = 1$, it found that $C = 0.38$. When $k \neq 1$, assume tank fire puffing frequency is in agreement with Eq. (6) too, we can calculate the tank fire frequency. Fig. 11 shows that calculation and experiments are in good agreement. So we can still use Eq. (6) to predict tank fire frequency even though the flame shape is not like pool fire.

3.4. Flame radiation and tank-shell temperature

Table 4 compares the radiation intensity of open end side and opposite side. Measure points lay 5 times tank diameter from the tank centre. From Table 4 we can see that, the flame radiation and reduced as the opening became small, and there are obvious difference between the open end side and the opposite side. For easy observation, Fig. 11 set $\dot{q}''_A / \dot{q}''_B$ as y-axis, k as x-axis. It could be seen that when opening proportion decreased from 1 to 1/8, $\dot{q}''_A / \dot{q}''_B$ exponentially increased from 1 to 3.

Table 4. The flame radiation of oil tank fire at a series of opening proportion

k	Radiation intensity of open end side $\dot{q}''_A$ (W/m^2)	Radiation intensity of opposite side $\dot{q}''_B$ (W/m^2)
1	505	499
1/2	228	197
1/4	42	26
1/8	12	4

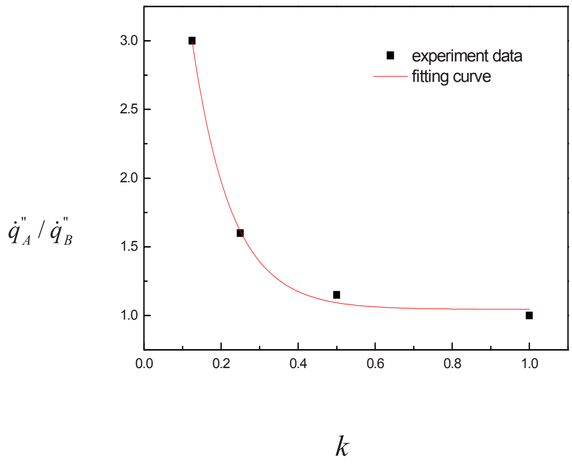

Fig. 12. $\dot{q}''_A / \dot{q}''_B$ of oil tank fire at a series of opening proportion.

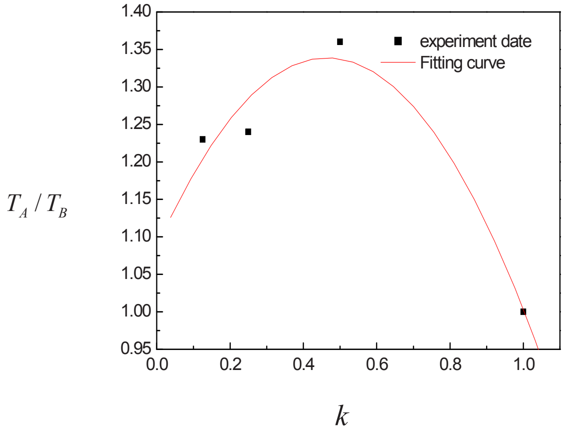

Fig. 13. T_A / T_B of oil tank fire at a series of opening proportion.

It means that while the tank top opening is small, the radiation of opposite side is much smaller than that of open end side. These differences are caused by asymmetries of opening area to the tank top. This phenomenon may be very important while an actual oil tank fire occurs. That means when oil tank on fire, man in the open end side have a greater chance of being burned as people in the opposite side.

Likewise, Table 5 compared the tank-shell temperature of open end side and opposite side. Like flame radiation, tank-shell temperature reduced as the opening became small, and the open end tank-shell temperature is higher than opposite side. But not like the radiation, T_A / T_B is not decreasing drably. It initially increases, reaches a maximal value at 0.5 and then decreases. These could be seen in Fig. 13.

Table 5. The tank-shell temperature at a series of opening proportion

k	temperature of open end side tank-shell (°C)	temperature of opposite side tank-shell (°C)
1	198	197
1/2	173	127
1/4	115	93
1/8	107	87

4. Conclusions

A series of tank fires with different top openings were burned in a still environment, with diesel as the fuel, to test mass loss rate, fire shape, fire frequency and flame height for different opening proportions. This paper analyzes the relationship between tank fire and pool fire in depth based on the experiment. Results indicated that the mass loss rate of diesel tank fire showed similarity to pool fire with the same equivalent diameter, the experimental result is in agreement with that of pool fire empirical equation. Tank fire frequency is in good agreement with calculation by pool fire classic theory. The difference is that for pool fire, the proportionality factor C=0.48, for diesel tank fire C=0.38. Flame heights of tank fire mainly keep consistent with pool fire for the same equivalent diameter. But when k approaches 0, experiment result is obviously lower than calculation significantly, because for tank fire the heat release is useful for not only sustaining combustion but also keeping surrounding liquid high temperature. Opening eccentricities influence the tank fire characters too. When k=1, the flame shape has no difference with pool fire; while k<1, and Opening eccentricities is significantly greater than 0, fire puffing mainly happened on the open side, flame shows unsymmetrical but L-shaped. Opening eccentricities could greatly affect the surrounding radiation intensity and tank-shell temperature. While k approaches 0 the radiation intensity and tank-shell temperature of open end side are significantly greater than those of opposite side.

Acknowledgements

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